Recent results on hadron spectroscopy at LHCb

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- Summary and prospects

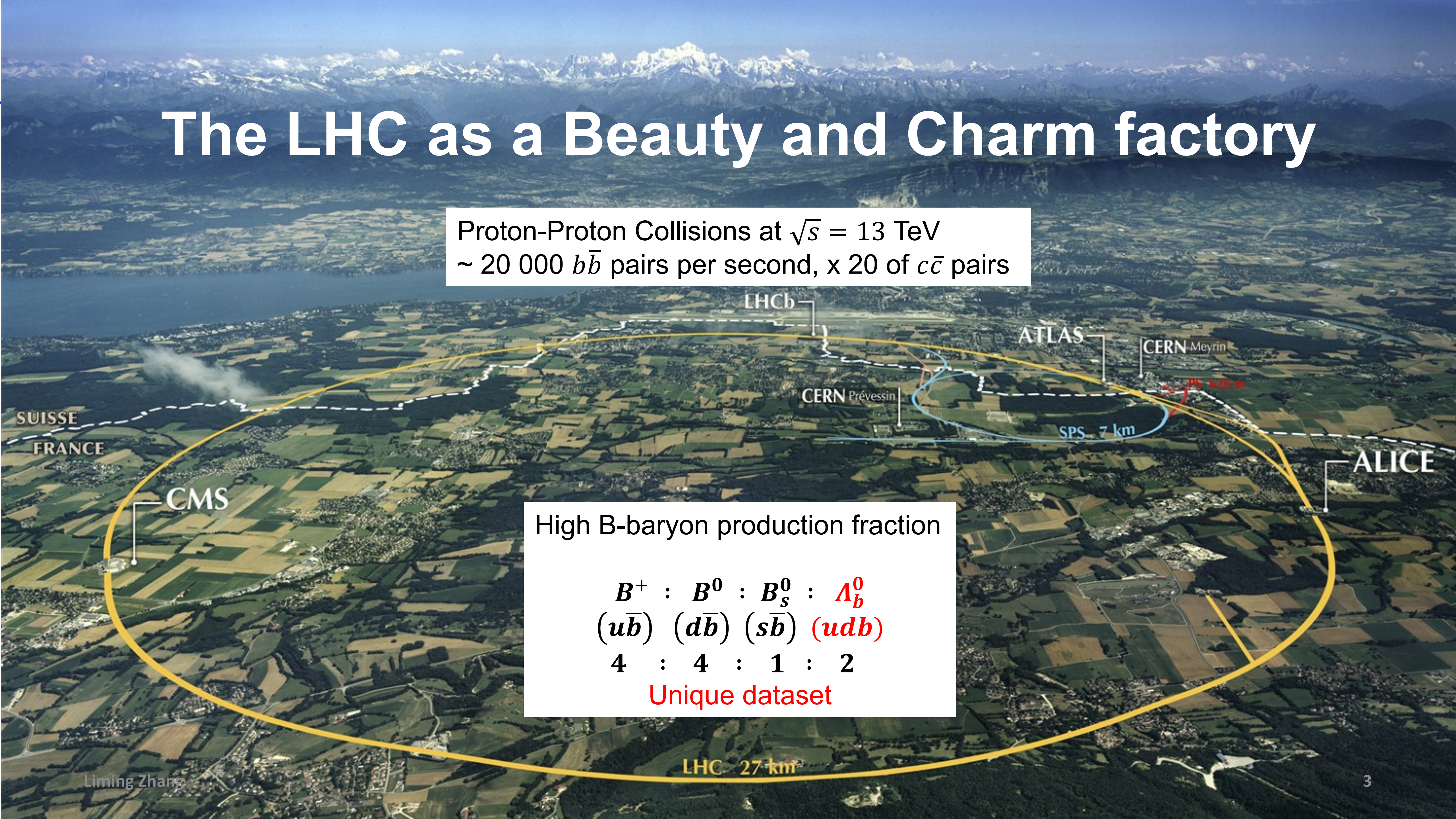
The LHC as a Beauty and Charm factory

Proton-Proton Collisions at $\sqrt{s} = 13$ TeV
~ 20 000 $b\bar{b}$ pairs per second, x 20 of $c\bar{c}$ pairs

High B-baryon production fraction

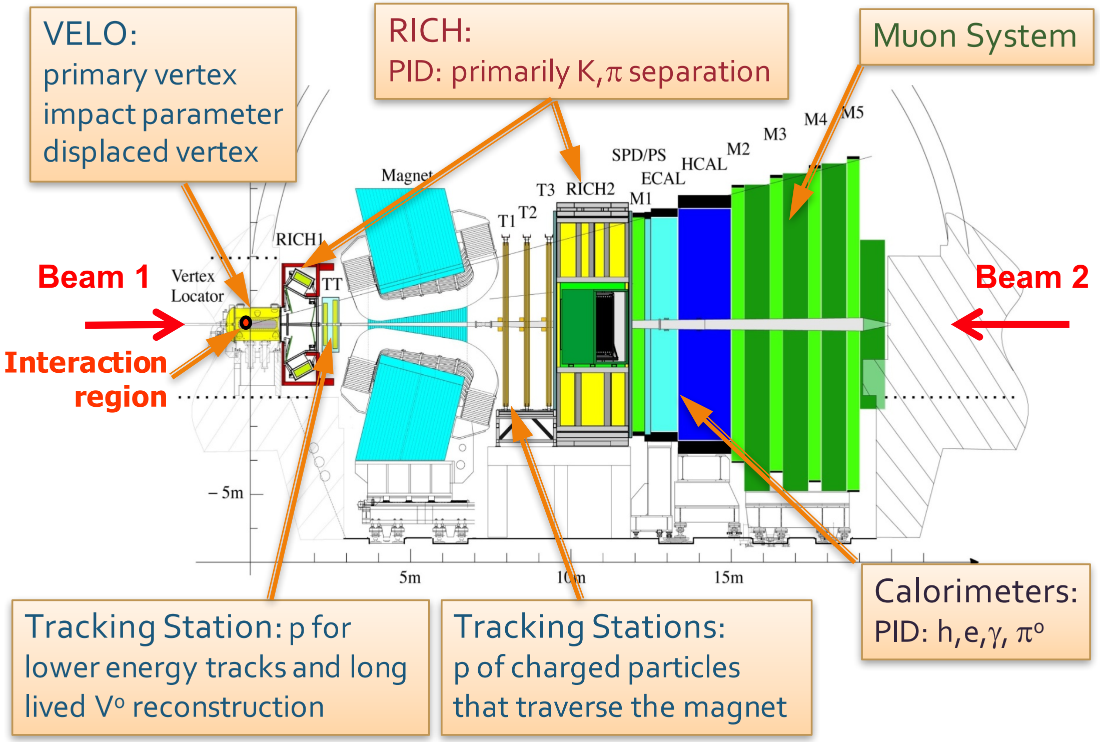
$$B^+ : B^0 : B_s^0 : \Lambda_b^0$$
$$(u\bar{b})\ (d\bar{b})\ (s\bar{b})\ (udb)$$
$$4 : 4 : 1 : 2$$

Unique dataset

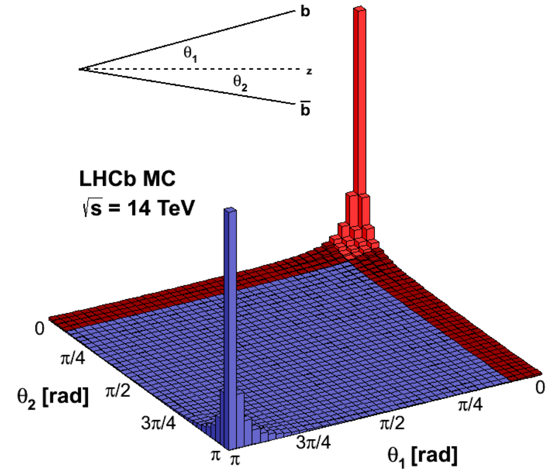


LHCb detector and performance

The LHCb detector described in [JINST 3 (2008) S08005]



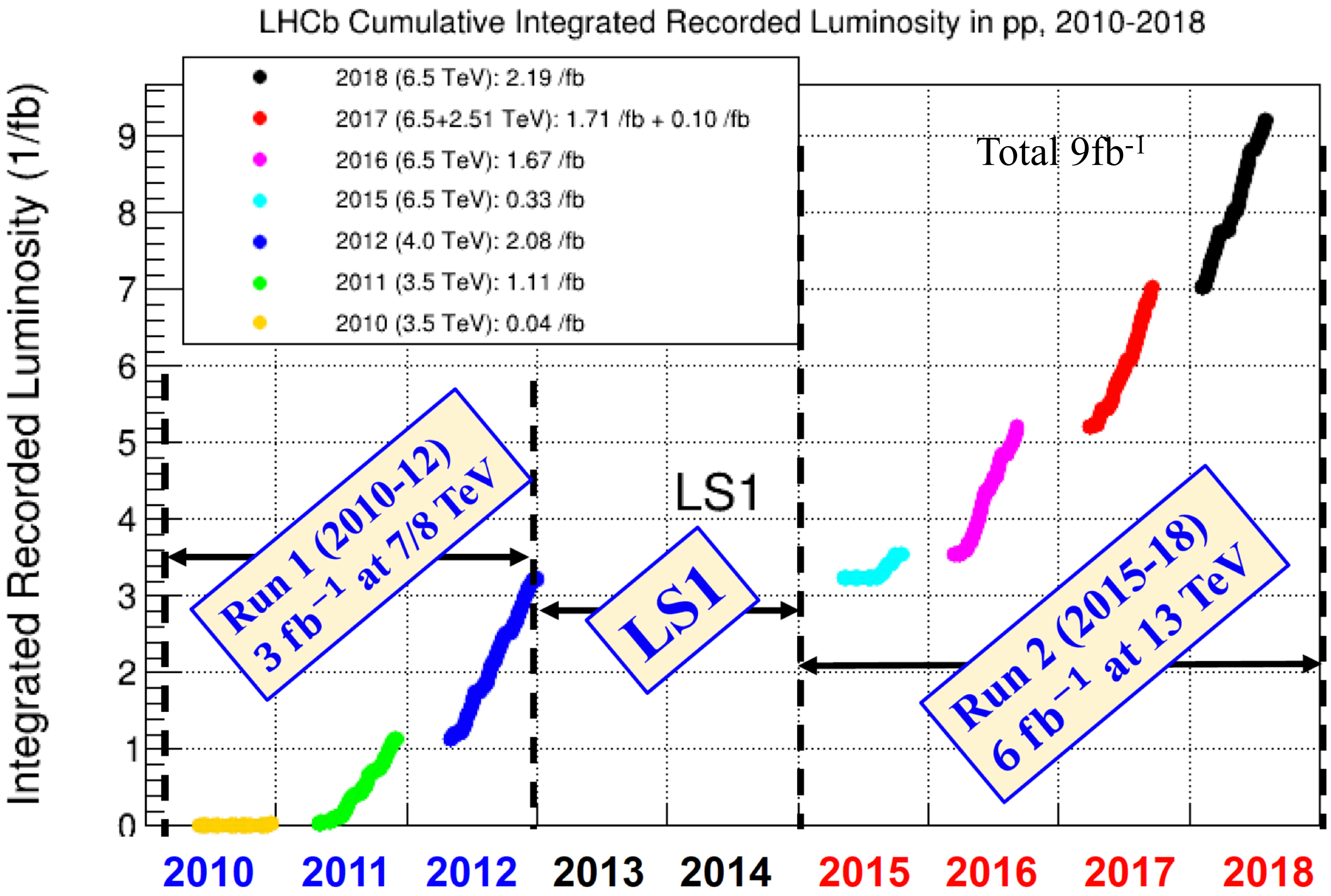
- $2 < \eta < 5$ range: $\sim 25\%$ of $b\bar{b}$ pairs inside LHCb acceptance



[Int. J. Mod. Phys. A 30 (2015) 1530022]

Impact parameter:	$\boldsymbol{\sigma_{IP} = 20\ \mu m}$
Proper time:	$\sigma_\tau = 45$ fs for $B_s^0 \to J/\psi\phi$ or $D_s^+\pi^-$
Momentum:	$\Delta p/p = 0.4 \sim 0.6\%$ (5 – 100 GeV/c)
Mass :	$\boldsymbol{\sigma_m = 8\ \mathrm{MeV}/c^2}$ **for** $\boldsymbol{B \to J/\psi X}$ **(constrained** $\boldsymbol{m_{J/\psi}}$**)**
RICH $K-\pi$ separation:	$\boldsymbol{\epsilon(K \to K) \sim 95\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to K) \sim 5\%}$
Muon ID:	$\boldsymbol{\epsilon(\mu \to \mu) \sim 97\%}$ **mis-ID** $\boldsymbol{\epsilon(\pi \to \mu) \sim 1-3\%}$
ECAL:	$\Delta E/E = 1 \oplus 10\%/\sqrt{E(\mathrm{GeV})}$

LHCb collected luminosity



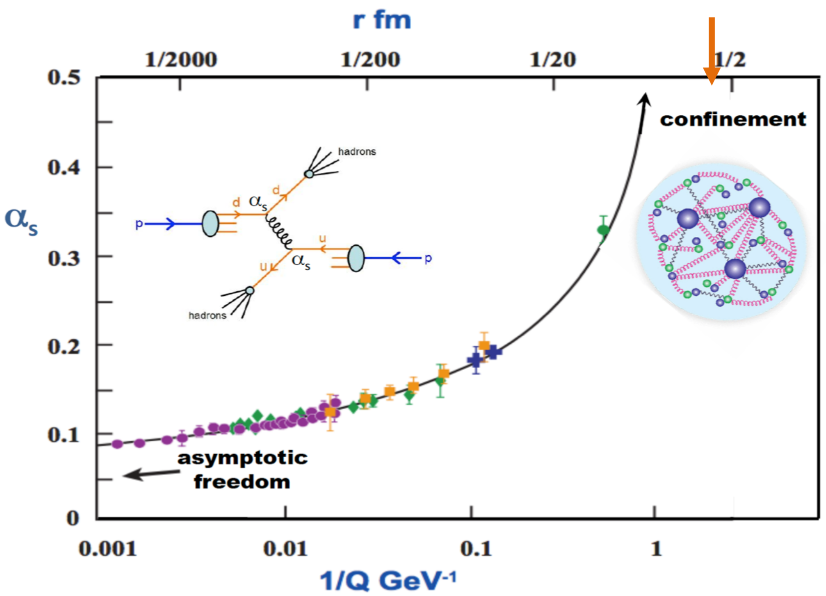
Signal: Run2 = 4× Run1

Such large samples, we are able to observe exotic states in fine structures, and see/observe exotics with strangeness

Introduction

- Hadron spectroscopy provides opportunities to study QCD in the non-perturbative region
  - Extensive and precise spectroscopy combined with a thorough theoretical analysis, will add substantially to our knowledge of QCD
- Complex exotic hadrons can reveal new or hidden aspects of the dynamics of strong interactions
  - Predicted in quark model
  - Recent results show strong evidence for their existence

Hardon size



【1】H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Phys. Rept. 639 (2016) 1-121.
【2】A. Ali, J. Lange, S. Stone, Prog. Part. Nucl. Phys. 97 (2017) 123-198.
【3】F.-K. Guo, C. Hanhart, U.-G. Meißner, Q. Wang, Q. Zhao and B.-S. Zou, Rev. Mod. Phys. 90 (2018) 015004.
【4】S. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 15003.
【5】Y.-R. Liu, H.-X. Chen, W. Chen, X. Liu and S.-L. Zhu, Prog. Part. Nucl. Phys. 107 (2019) 237-320.
【6】F.-K. Guo, X.-H. Liu and S. Sakai, Prog. Part. Nucl. Phys. 112 (2020) 103757
【7】X.-K Dong, F.-K. Guo, B.-S. Zou, arXiv:2101.01021

tetraquark ? pentaquark ? hybrid ?

… EXOTIC

Normal and exotic hadrons in $B \to D^{(*)}\bar{D}^{(*)}h(h')$

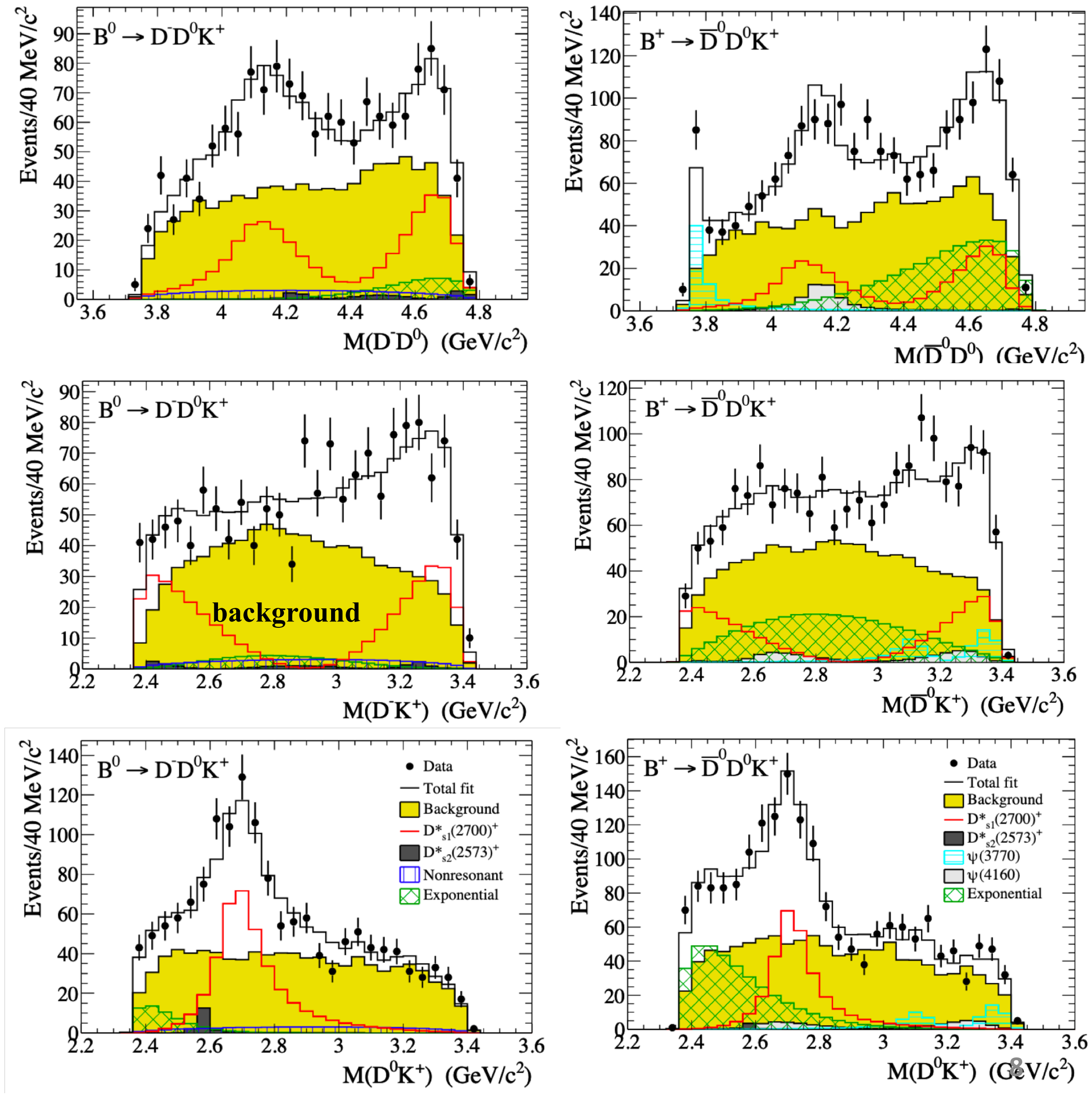
Why $B \to D^{(*)}\bar{D}^{(*)}h(h')$ decays

- Wide range of spectroscopy studies
  1. D_{sJ}^{+} spectroscopy, e.g. D^0K^+; $D^+K^+\pi^-$ [Fav]
  2. Open charm exotics; $D^+K^-[cs\bar{u}\bar{d}]$ **[Fav]**
  3. Charmonium, e.g. $D^{(*)}\bar{D}^{(*)}$ [Sup]
  4. Charmonium exotics, e.g. $Z_c^+ \to D^{*+}\bar{D}^0$ [Sup]

  Sup=Color-Suppress   Fav=Color-Favor

- Not yet well explored
  - B-factories used $B^0 \to D^-D^0K^+$ and $B^+ \to \bar{D}^0D^0K^+$ and determined the spin of $D_{s1}^*(2700)^+$

    [Belle, PRL 100 (2008) 092001]
  - About 800 signals, huge background, purity is only 40%

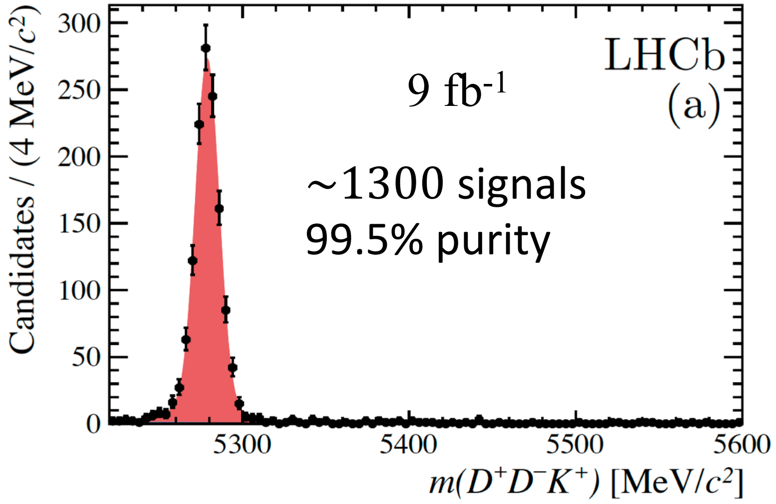


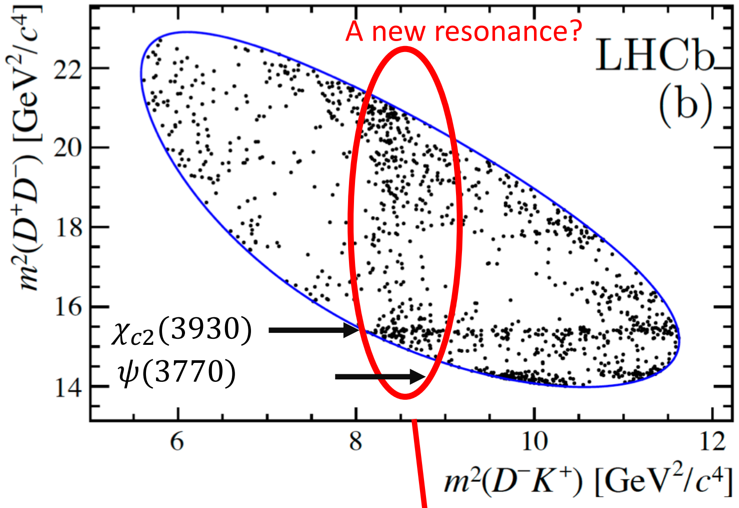
[Babar, PRD 91 (2015) 052002]

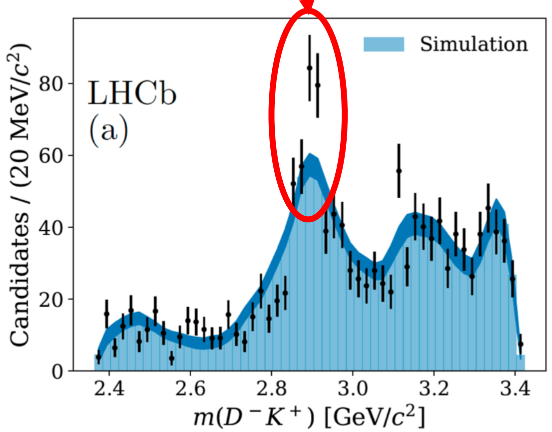
$B^+ \to D^+ D^- K^+$ decays from LHCb

Γ_{197}	$\overline{D}^0 D^0 K^+$	$(1.45 \pm 0.33) \times 10^{-3}$
Γ_{201}	$D^- D^+ K^+$	$(2.2 \pm 0.7) \times 10^{-4}$

- $B^+ \to D^+ D^- K^+$ decay:
  - Ideal channel to search for the open-charm tetraquark
  - Contributions: no Fav D_{sJ}^+, Sup charmonium, Fav open-charm tetraquark(?)







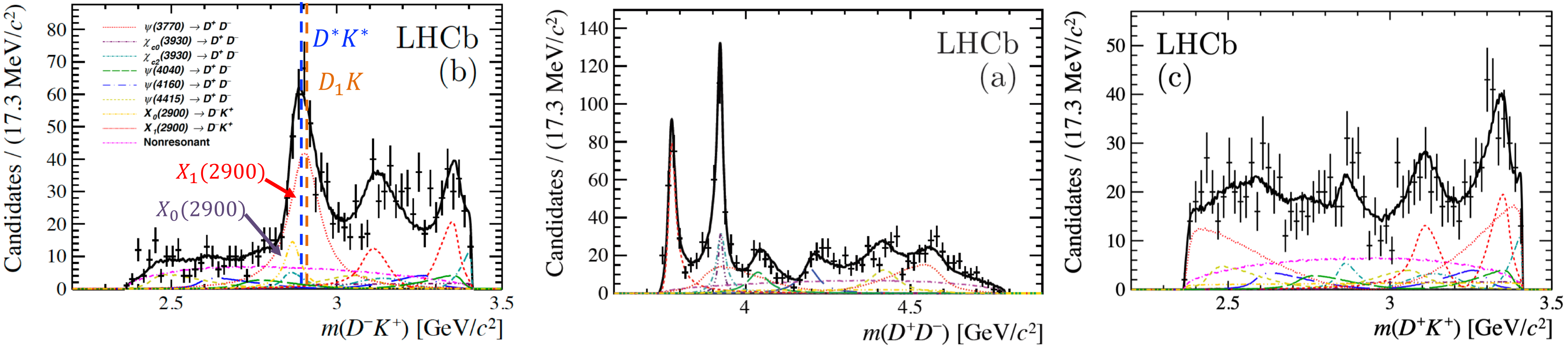
[PRL 125 (2020) 242001]

- Model-independent study
  - Hypothesis with only $D^+ D^-$ resonances ($J_{\max} = 2$) is rejected by 3.9σ
  - Indicate the existence of exotic contributions

Observation of D^-K^+ ($\bar{c}\bar{s}ud$) structure

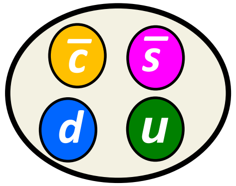
[PRD 102 (2020) 112003]

- Add two D^-K^+ states (BW) at ~ 2.9 GeV, $J^P=0^+, 1^-$
  - Improve $2\ln\mathcal{L}$ by >300 units



- Need more intricate theoretical studies
  - Very close to D^*K^*, D_1K thresholds. Rescattering ?

Candidates for the 1st open-charm tetraquarks (four different flavors)!



States	Mass/MeV	Width/MeV	Fraction/%
$X_0(2900)$	$2866 \pm 7 \pm 2$	$57 \pm 12 \pm 4$	$5.6 \pm 1.4 \pm 0.5$
$X_1(2900)$	$2904 \pm 5 \pm 1$	$110 \pm 11 \pm 4$	$30.6 \pm 2.4 \pm 2.1$

Quite large contribution!

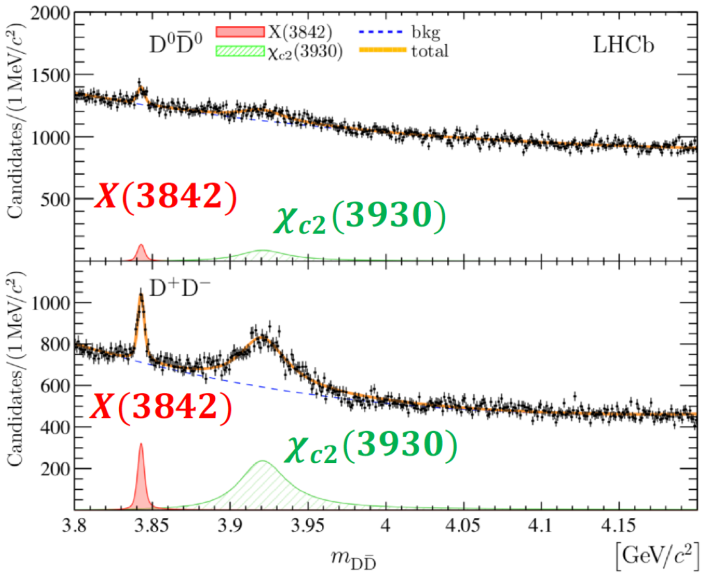
Puzzles around 3930 MeV

Summary of current PDG

$D_s^+ D_s^-$ threshold: 3936.68 MeV

	J^{PC}	Mass(MeV)	Width(MeV)	Decays
$X(3915)$	$0^{++}/2^{++}$	3918.4 ± 1.9	20 ± 5	$J/\psi\omega, \gamma\gamma$
$\chi_{c2}(3930)$	2^{++}	3922.2 ± 1.0	35.3 ± 2.8	$D\bar{D}, \gamma\gamma$

- LHCb prompt $D\bar{D}$ results



[JHEP 07 (2019) 035]

		$m_{\chi_{c2}(3930)}$ [MeV/c^2]	$\Gamma_{\chi_{c2}(3930)}$ [MeV]
Belle	[17]	$3929 \pm 5 \pm 2$	$29 \pm 10 \pm 2$
BaBar	[18]	$3926.7 \pm 2.7 \pm 1.1$	$21.3 \pm 6.8 \pm 3.6$
This analysis		$3921.9 \pm 0.6 \pm 0.2$	$36.6 \pm 1.9 \pm 0.9$

- LHCb measurements from inclusive DD channels show difference on the mass and width, 2σ lower mass and 2σ larger width
- Current PDG values driven by LHCb inclusive measurements

Inputs from $B^+ \to D^+ D^- K^+$

Summary of current PDG

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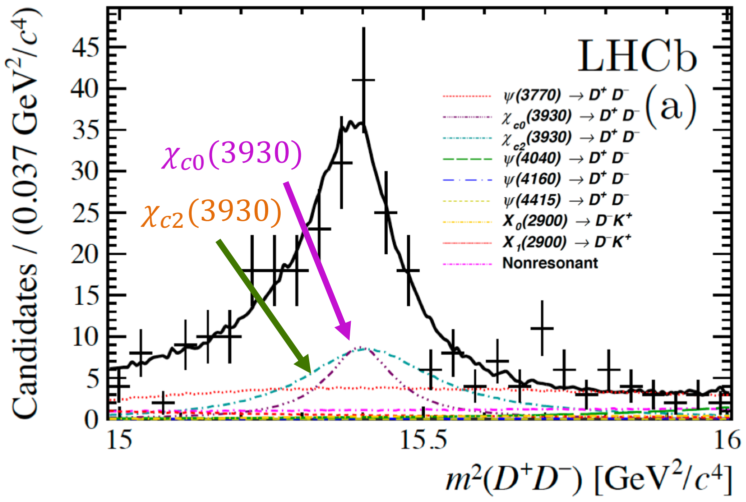
$\chi_{c2}(3930)$	2^{++}	3922.2 ± 1.0	35.3 ± 2.8	$D\bar{D}, \gamma\gamma$

- Interesting inputs

[PRD 102 (2020) 112003]

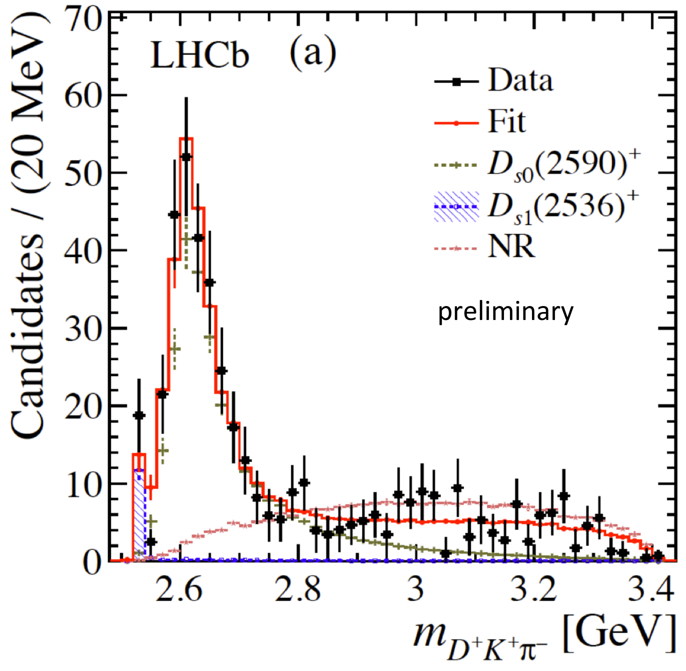


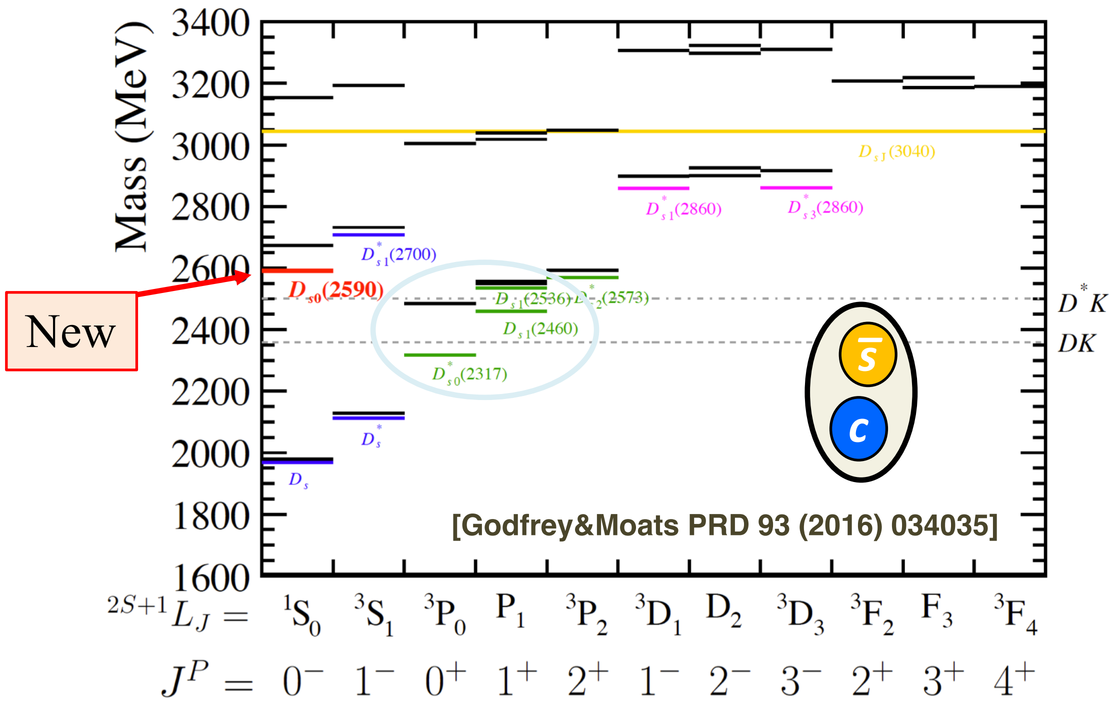
Resonance	Mass (GeV/c^2)	Width (MeV)
$\chi_{c0}(3930)$	$3.9238 \pm 0.0015 \pm 0.0004$	$17.4 \pm 5.1 \pm 0.8$
$\chi_{c2}(3930)$	$3.9268 \pm 0.0024 \pm 0.0008$	$34.2 \pm 6.6 \pm 1.1$

- Two resonances seen in DD decays, with J=0 and J=2; lead to rethink of previous results
- It also puts the question whether this spin 0 particle = $X(3915)$?

A new D_s^+ state from $B^0 \to D^+ D^- K^+ \pi^-$ [arXiv:2011.09112]

- Big puzzle: $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ have much smaller masses than the predictions
- Additional experimental input is helpful
- Use $B^0 \to D^+ D^- K^+ \pi^-$ decay
  - $m(K^+\pi^-) < 0.75$ GeV consistent with S-wave $K^+\pi^-$
- $D^+ K^+ \pi^-$ invariance mass shows a strong peak





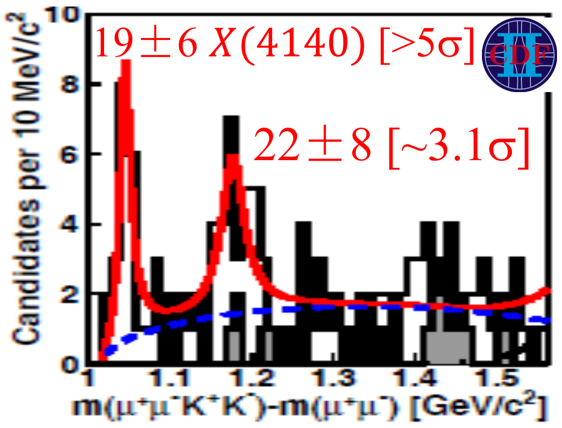
- Amplitude fit is performed

State	Pole Mass [MeV]	Pole Width [MeV]	J^P
$D_{s0}(2590)^+$	$2591 \pm 6 \pm 7$	$89 \pm 16 \pm 12$	0^-

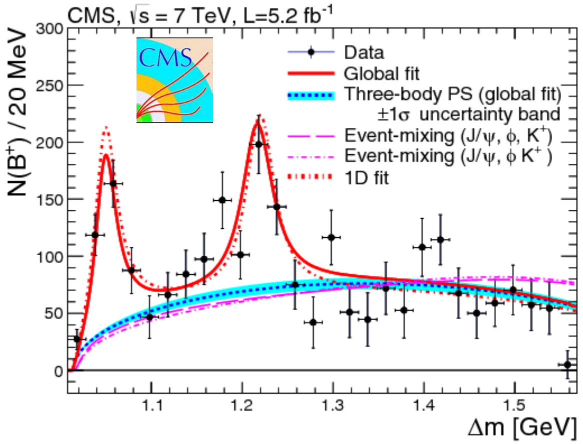
Tetraquarks in $J/\psi\phi$ $[c\bar{c}s\bar{s}]$ systems

$X \to J/\psi\phi$ in $B^+ \to J/\psi\phi K^+$ decays

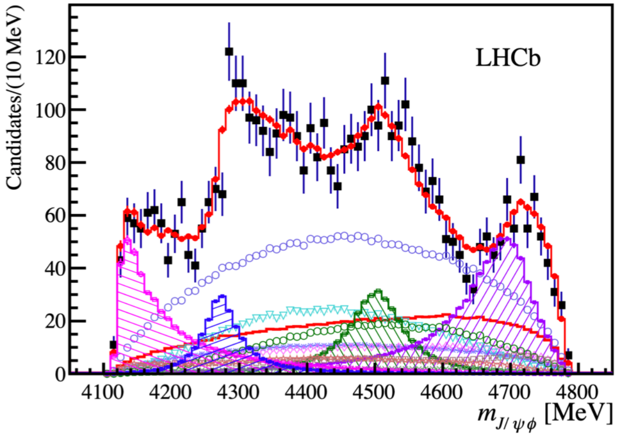
- Provide rich exotic states



PRL102(2009)242002
arXiv:1101.6058



PLB734(2014)261



PRD95(2017)012002
PRL118(2017)022003

States	J^{PC}	Mass/MeV	Width/MeV	Signi.	Experiment	Nearest thresholds
$X(4140)$	1^{++}	$4143.4 \pm 3.0 \pm 0.6$	$15.3^{+10.4}_{-6.1} \pm 2.5$	>5σ	CDF	$D_s^+ D_s^{*-}$: 4080
		$4148.0 \pm 2.4 \pm 6.3$	$28^{+15}_{-11} \pm 19$	>5σ	CMS	
		$4146.5 \pm 4.5^{+4.6}_{-2.8}$	$83 \pm 21^{+21}_{-14}$	8.4σ	LHCb	
$X(4274)$	1^{++}	$4274.4^{+8.4}_{-6.7} \pm 1.9$	$32.3^{+21.9}_{-15.3} \pm 7.6$	3.1σ	CDF	$D_s^+ D_{s0}^*(2317)^-$: 4286
		$4313.8 \pm 5.3 \pm 7.3$	$28^{+15}_{-11} \pm 19$	>3σ	CMS	
		$4273.3 \pm 8.3^{+17.2}_{-3.6}$	$56.2 \pm 10.9^{+8.4}_{-11.1}$	6.0σ	LHCb	
$X(4500)$	0^{++}	$4506 \pm 11^{+12}_{-15}$	$92 \pm 21^{+21}_{-20}$	6.1σ	LHCb	$D_s^+ D_{s1}^*(2536)^-$: 4503
$X(4700)$	0^{++}	$4704 \pm 10^{+14}_{-24}$	$120 \pm 31^{+42}_{-33}$	5.6σ	LHCb	$D_s^{*+} D_{s2}^*(2573)^-$: 4681

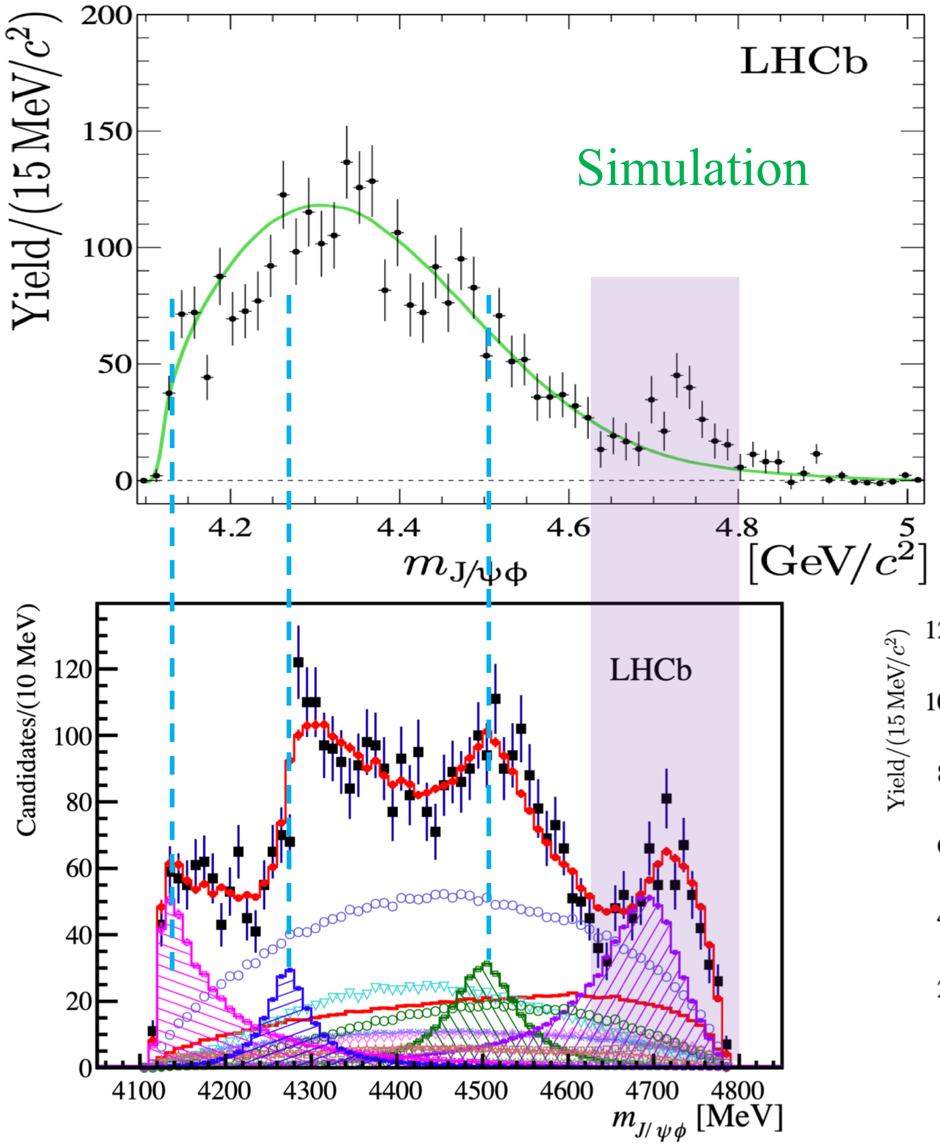
60 MeV

P = −

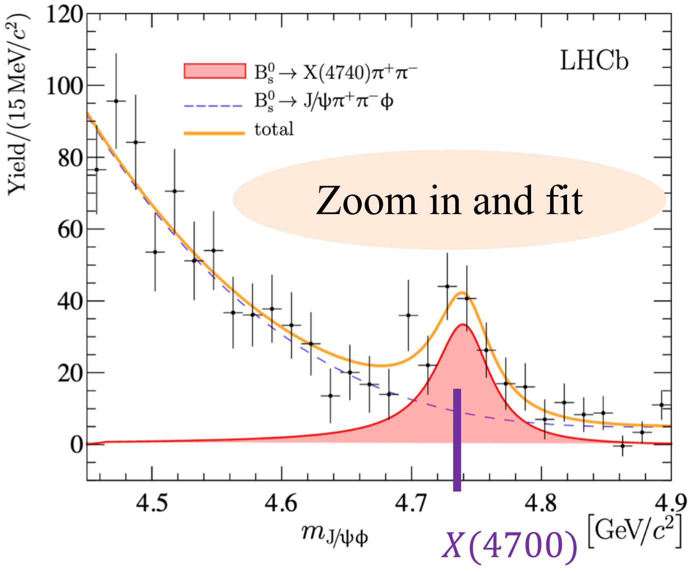
Updated analysis with full LHCb data will be out next month

New $X(4740)$ structure

[arXiv:2011.01867]



- $B_s^0 \to J/\psi\phi\pi^+\pi^-$ decay is studied
- No clear $X(4140)$ peak
- $X(4740)$?
  - Could be the $X(4700)$ in $B^+ \to J/\psi\phi K^+$
  - Amplitude fit is needed to resolve, e.g. determining mass, width and J^P



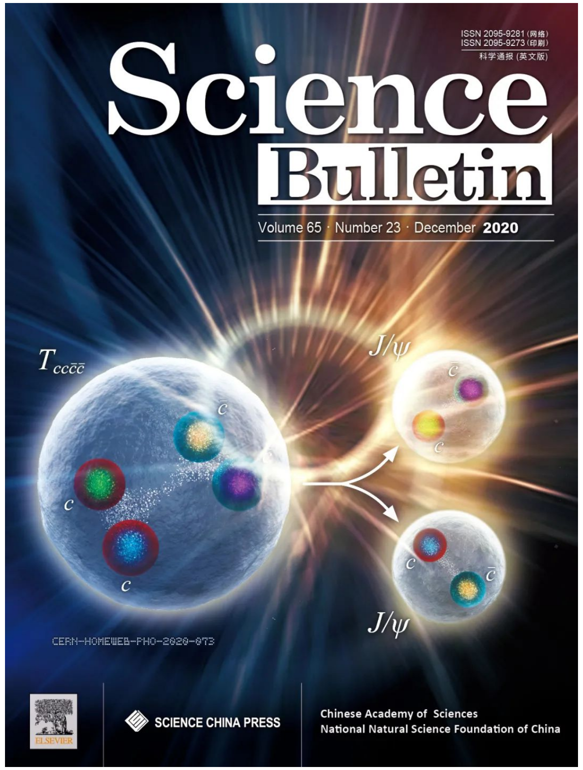
- 1D fit using S-wave Breit-Wigner

$$m_{X(4740)} = 4741 \pm 6 \pm 6 \text{ MeV}$$
$$\Gamma_{X(4740)} = 53 \pm 15 \pm 11 \text{ MeV}$$

Systematic uncertainties:

- Shape of underlying non-X
- Alternative P-wave or D-wave BW
- Inteference $\mathcal{F}_S(m_{J/\psi\phi}) \propto \left|\mathcal{A}(m_{J/\psi\phi}) + b(m_{J/\psi\phi})\,e^{i\varphi}\right|^2$

Full charmed states



$T_{cc\bar{c}\bar{c}}$ not new

Y. Iwasaki, *Is a state $c\bar{c}c\bar{c}$ found at 6.0 GeV?*, Phys. Rev. Lett. **36** (1976) 1266.

K.-T. Chao, *The (cc) - $(\bar{c}\bar{c})$ (diquark-antidiquark) states in e^+e^- annihilation*, Z. Phys. C **7** (1981) 317.

…

J. Wu *et al.*, *Heavy-flavored tetraquark states with the $QQ\bar{Q}\bar{Q}$ configuration*, Phys. Rev. **D97** (2018) 094015, arXiv:1605.01134.

M.-S. Liu, Q.-F. L, X.-H. Zhong, and Q. Zhao, *All-heavy tetraquarks*, Phys. Rev. **D100** (2019) 016006, arXiv:1901.02564.

G.-J. Wang, L. Meng, and S.-L. Zhu, *Spectrum of the fully-heavy tetraquark state $QQ\bar{Q}'\bar{Q}'$*, Phys. Rev. D **100** (2019) 096013, arXiv:1907.05177.

M. A. Bedolla, J. Ferretti, C. D. Roberts, and E. Santopinto, *Spectrum of fully-heavy tetraquarks from a diquark+antidiquark perspective*, arXiv:1911.00960.

X. Chen, *Fully-charm tetraquarks: $cc\bar{c}\bar{c}$*, arXiv:2001.06755.

- Many papers predicted many such states
- Predictions: Mass mostly below 7 GeV

PLB 773 (2017) 247

J^{PC}	m_{X_c} (GeV)
0^{++}	6.44 ± 0.15
	6.59 ± 0.17
	6.47 ± 0.16
	6.46 ± 0.16
	6.82 ± 0.18
0^{-+}	6.84 ± 0.18
	6.85 ± 0.18
0^{--}	6.84 ± 0.18
1^{++}	6.40 ± 0.19
	6.34 ± 0.19
1^{+-}	6.37 ± 0.18
	6.51 ± 0.15
1^{-+}	6.84 ± 0.18
	6.88 ± 0.18
1^{--}	6.84 ± 0.18
	6.83 ± 0.18
2^{++}	6.51 ± 0.15
	6.37 ± 0.19

arXiv:1911.00960

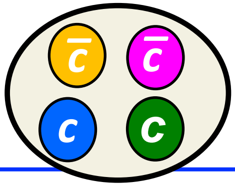
	$cc\bar{c}\bar{c}$	
J^{PC}	$N[(S_D, S_{\bar{D}})S, L]J$	E^{th} [MeV]
0^{++}	1[(1, 1)0, 0]0	5883
0^{++}	2[(1, 1)0, 0]0	6573
0^{++}	1[(1, 1)2, 2]0	6835
0^{++}	3[(1, 1)0, 0]0	6948
0^{++}	2[(1, 1)2, 2]0	7133
0^{++}	3[(1, 1)2, 2]0	7387
1^{+-}	1[(1, 1)1, 0]1	6120
1^{+-}	2[(1, 1)1, 0]1	6669
1^{+-}	1[(1, 1)1, 2]1	6829
1^{+-}	3[(1, 1)1, 0]1	7016
1^{+-}	2[(1, 1)1, 2]1	7128
1^{+-}	3[(1, 1)1, 2]1	7382
1^{--}	1[(1, 1)0, 1]1	6580
1^{--}	1[(1, 1)2, 1]1	6584
1^{--}	2[(1, 1)0, 1]1	6940
1^{--}	2[(1, 1)2, 1]1	6943
1^{--}	3[(1, 1)0, 1]1	7226
1^{--}	3[(1, 1)2, 1]1	7229
0^{-+}	1[(1, 1)1, 1]0	6596
0^{-+}	2[(1, 1)1, 1]0	6953
0^{-+}	3[(1, 1)1, 1]0	7236
1^{++}	1[(1, 1)2, 2]1	6832
1^{++}	2[(1, 1)2, 2]1	7130
1^{++}	3[(1, 1)2, 2]1	7384
2^{++}	1[(1, 1)2, 0]2	6246
2^{++}	1[(1, 1)2, 2]2	6827
2^{++}	1[(1, 1)0, 2]2	6827
2^{++}	2[(1, 1)2, 0]2	6739
2^{++}	3[(1, 1)2, 0]2	7071
2^{++}	2[(1, 1)2, 2]2	7125
2^{++}	2[(1, 1)0, 2]2	7126
2^{++}	3[(1, 1)2, 2]2	7380
2^{++}	3[(1, 1)0, 2]2	7380

Some can decay to double-J/ψ

Directly or via feed-down

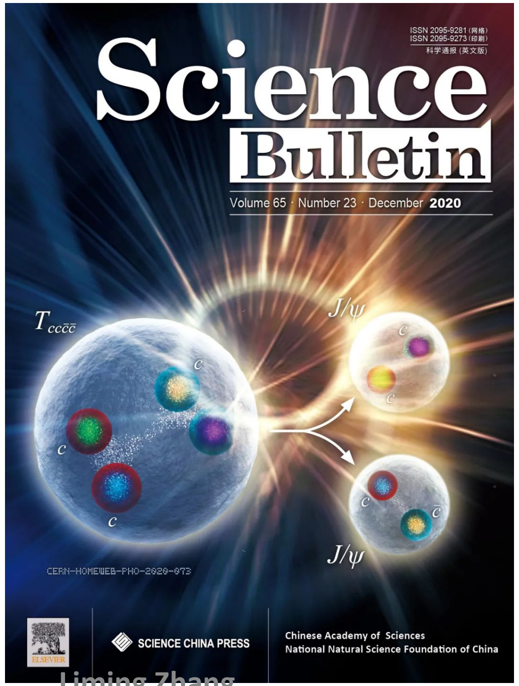
J^{PC}	S-wave	P-wave
0^{++}	$\eta_c(1S)\eta_c(1S)$, $J/\psi J/\psi$	$\eta_c(1S)\chi_{c1}(1P)$, $J/\psi h_c(1P)$
0^{-+}	$\eta_c(1S)\chi_{c0}(1P)$, $J/\psi h_c(1P)$	$J/\psi J/\psi$
0^{--}	$J/\psi\chi_{c1}(1P)$	$J/\psi\eta_c(1S)$
1^{++}	–	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$, $\eta_c(1S)\chi_{c0}(1P)$
1^{+-}	$J/\psi\eta_c(1S)$	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$
1^{-+}	$J/\psi h_c(1P)$, $\eta_c(1S)\chi_{c1}(1P)$	$\eta_c(1S)\chi_{c1}(1P)$ $J/\psi J/\psi$
1^{--}	$J/\psi\chi_{c0}(1P)$, $J/\psi\chi_{c1}(1P)$, $\eta_c(1S)h_c(1P)$	$J/\psi\eta_c(1S)$

$X(6900)$ in di-J/ψ system

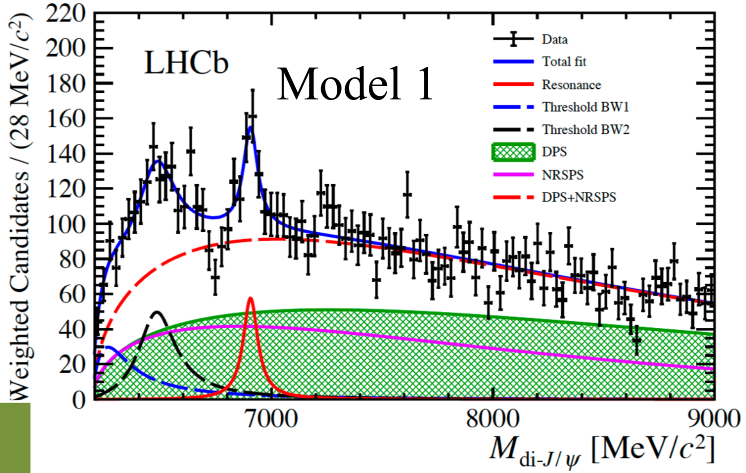


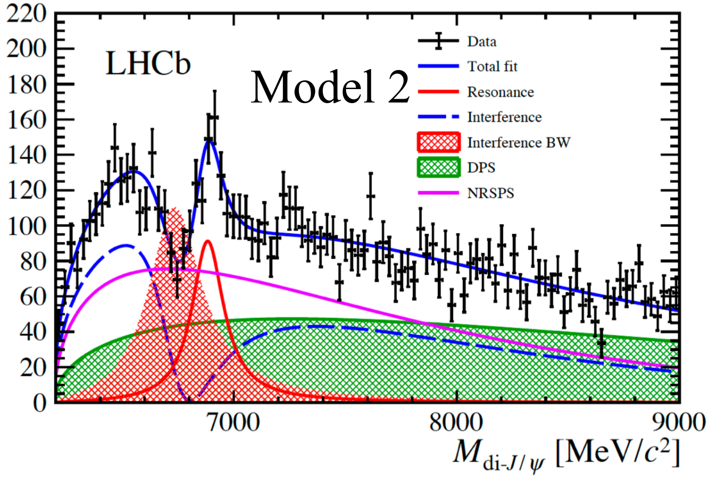
[Science Bulletin 65 (2020) 032]

- Search for di-J/ψ structure using full data
  - DPS + NRSPS cannot well describe data
  - A di-J/ψ resonance $X(6900)$ significantly improves the fit
  - Two fit models: both has $> 5\sigma$ significance of $X(6900)$
  - A first candidate for the $T_{cc\bar{c}\bar{c}}$ tetraquark state



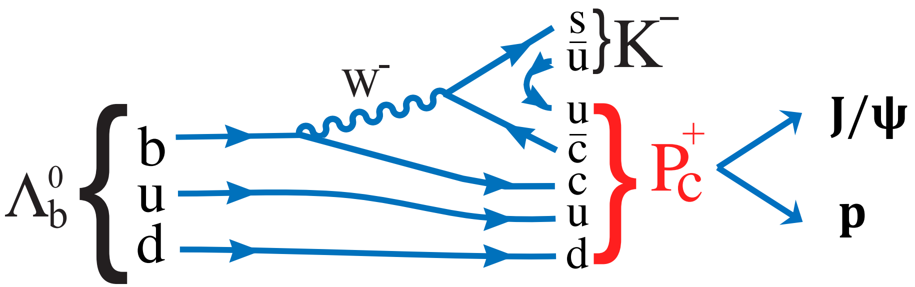
Model 1: No interference between NRSPS and BW
$M(6900) = 6905 \pm 11 \pm 7$ MeV
$\Gamma(6900) = 80 \pm 19 \pm 33$ MeV
Model 2: Interference between NRSPS and a broad BW
$M(6900) = 6886 \pm 11 \pm 11$ MeV
$\Gamma(6900) = 168 \pm 33 \pm 69$ MeV



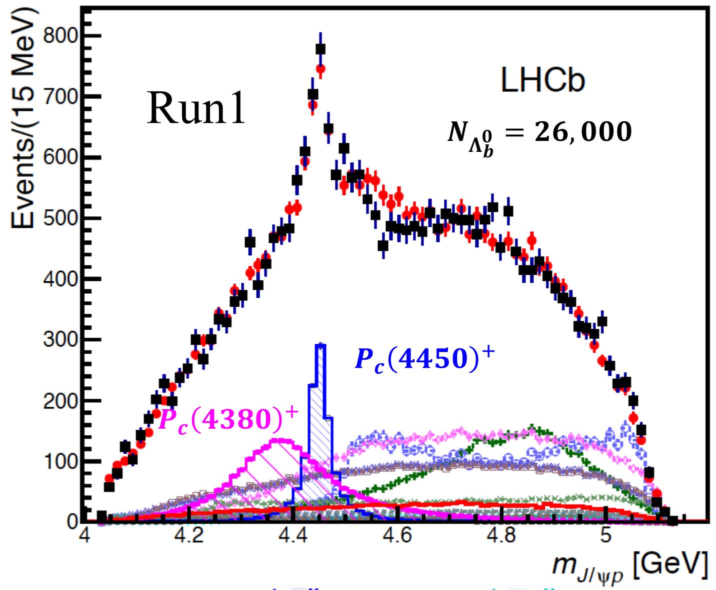


Hidden-charm pentaquarks

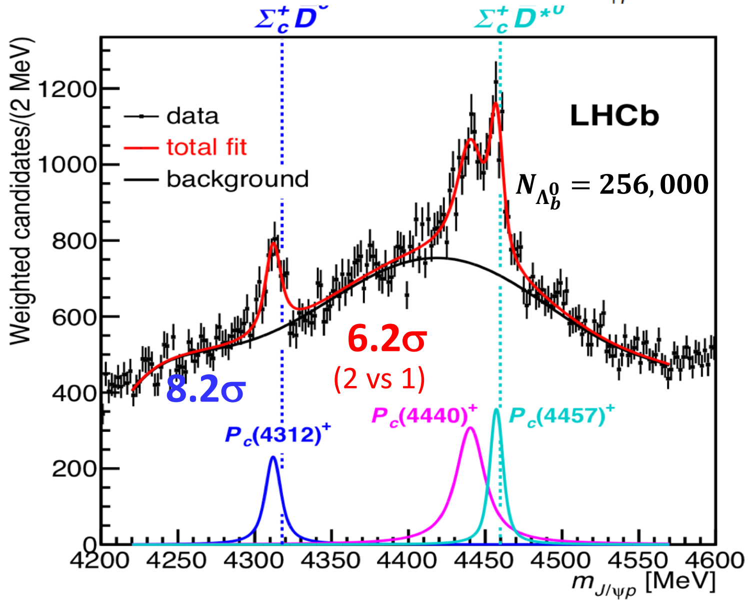
Pentaquarks in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays



- Pentaquarks was first observed in 2015 by LHCb in $\Lambda_b^0 \rightarrow J/\psi p K^-$ decays
- New pentaquark and fine structure was discovered in 2019 with x10 signals
  - Three narrow pentaquarks just below $\Sigma_c^+ D^{(*)0}$ thresholds, favours molecular picture
- A lot of open questions:
  - J^P, mode decay modes,…?
  - SU(3) partners, hidden-bottom pentaquarks?

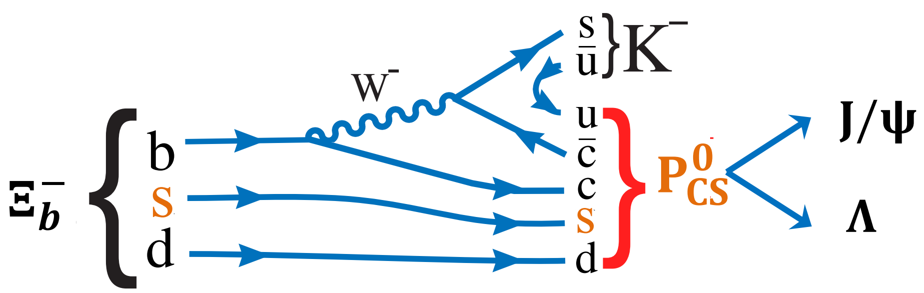


[PRL 115 (2015) 072001]



[PRL 122 (2019) 222001]

Evidence of $J/\psi\Lambda$ resonance: data sample



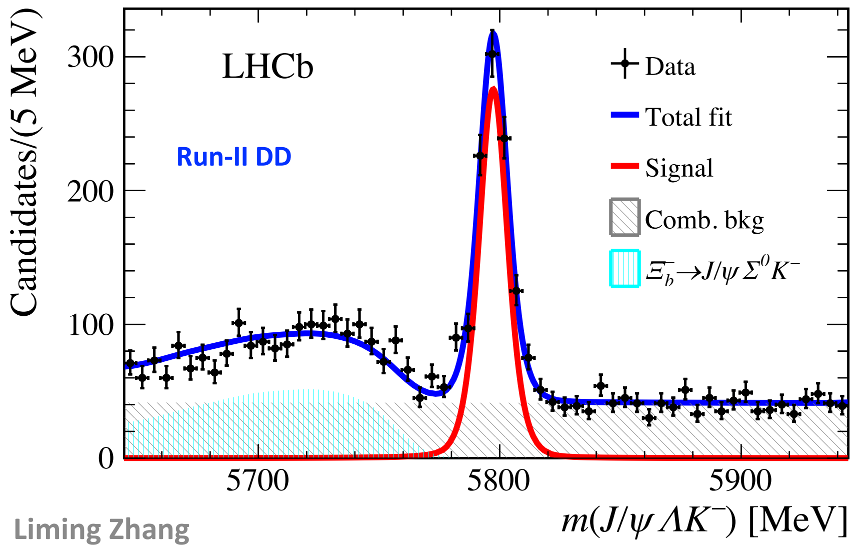
$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8\,\text{TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.5) \times 10^{-2} \quad [\sqrt{s} = 13\,\text{TeV}].$$

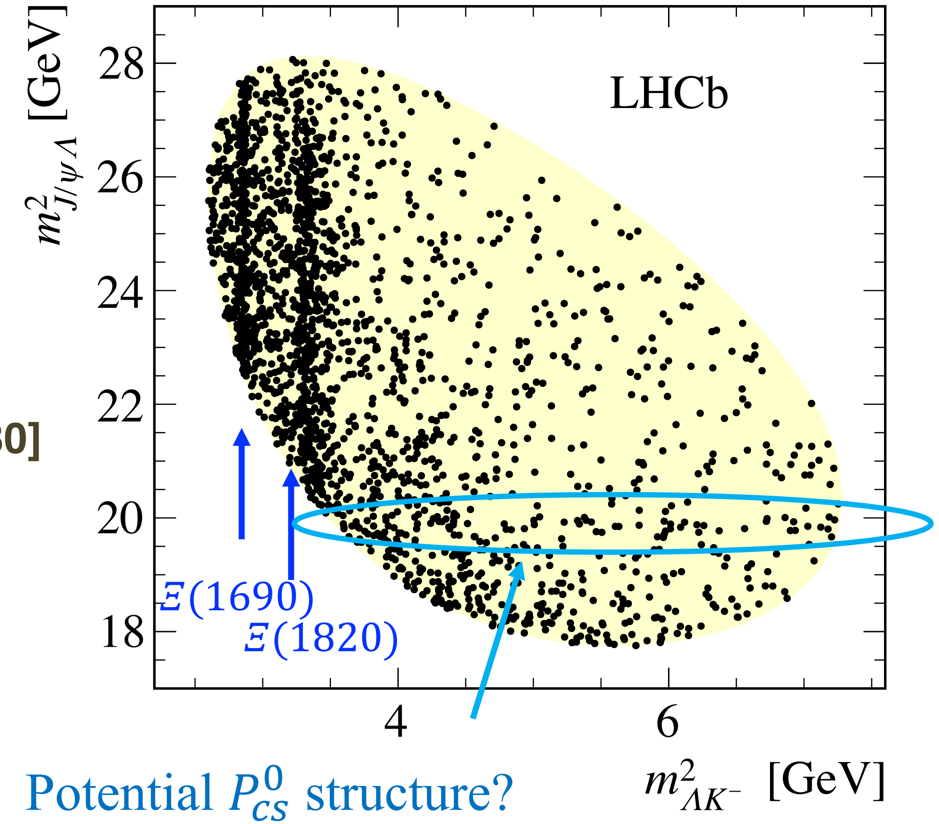
[LHCb, PRD 99 (2019) 052006]

- SU(3) partner P_{cs} is predicted, and suggested to search for in $\Xi_b^- \to J/\psi\Lambda K^-$
  [JJ Wu PRL 105 (2010) 232001; HX Chen PRC 93(2016) 064203]

~1750 $\Xi_b^- \to J/\psi\Lambda K^-$ signals (purity ~80%)



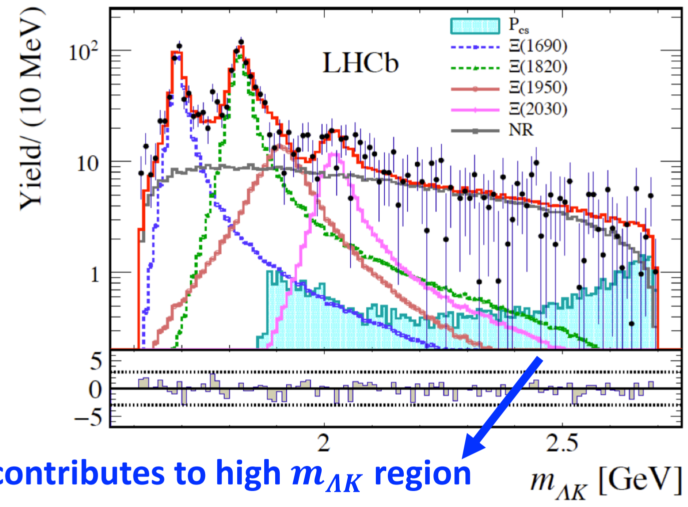
[arXiv:2012.10380]

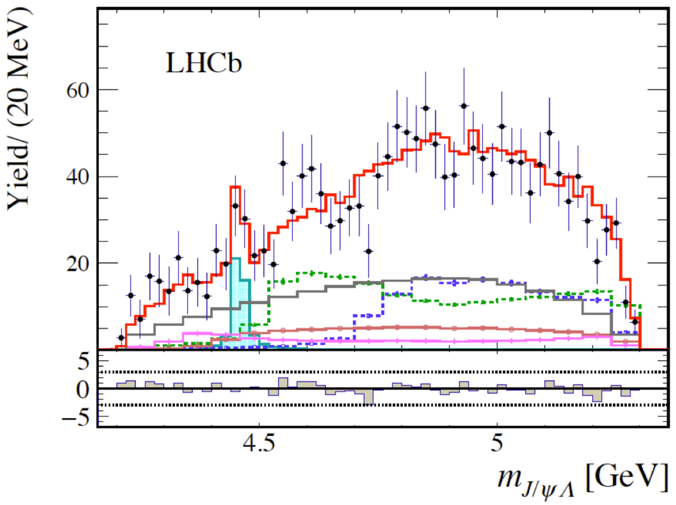


Potential P_{cs}^0 structure?
Full amplitude analysis is required

Evidence of $J/\psi\Lambda$ resonance: amplitude fit

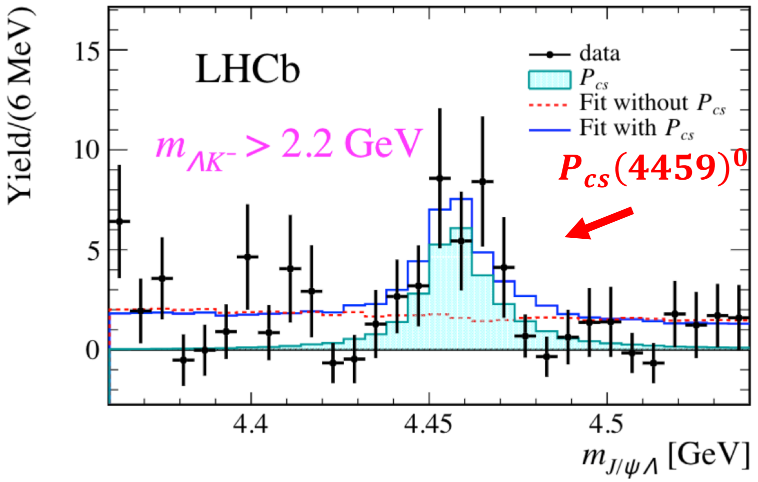
- Modelled by one P_{cs}^0
  - Adding a P_{cs} improves $2\ln\mathcal{L}$ by 43 units, statistical significance of $\mathbf{4.3\sigma}$ evaluated by toy experiments
  - Including various syst. uncertainty, the smallest significance is >3.1σ
  - Look-elsewhere effect is included in both cases
- Statistics not enough for J^P determination

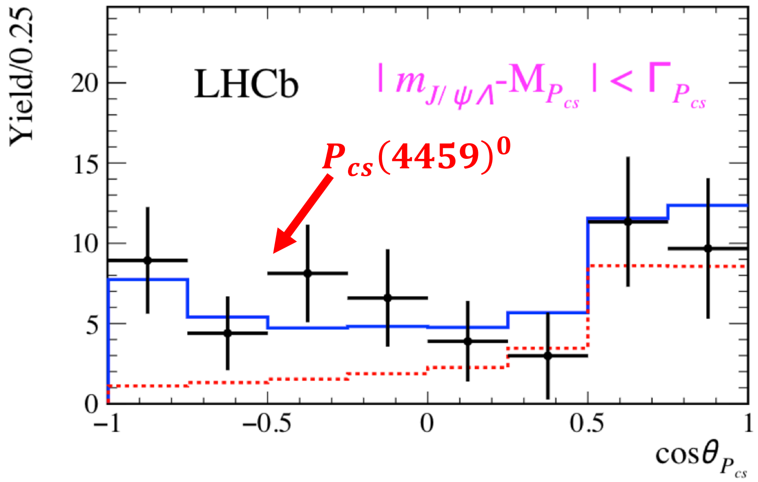




P_{cs}^0 contributes to high $m_{\Lambda K}$ region

Zooms in to P_{cs} signal region. Visible improvement.

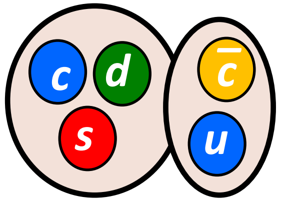




[arXiv:2012.10380]

- Molecular states built from $\Xi_c\bar{D}, \Xi_c'\bar{D}, \Xi_c^*\bar{D}, \Xi_c\bar{D}^*, \Xi_c'\bar{D}^*, \Xi_c^*\bar{D}^* \ldots$
  - Isospin-isospin interactions, vanish for $\bar{D}\Lambda_c^+$, $\bar{D}_s^*\Lambda_c^+$ $D_s^{*-}\Sigma_c^+$ …

[Bo Wang, Lu Meng, Shi-Lin Zhu, PRD 101 (2020) 034018]



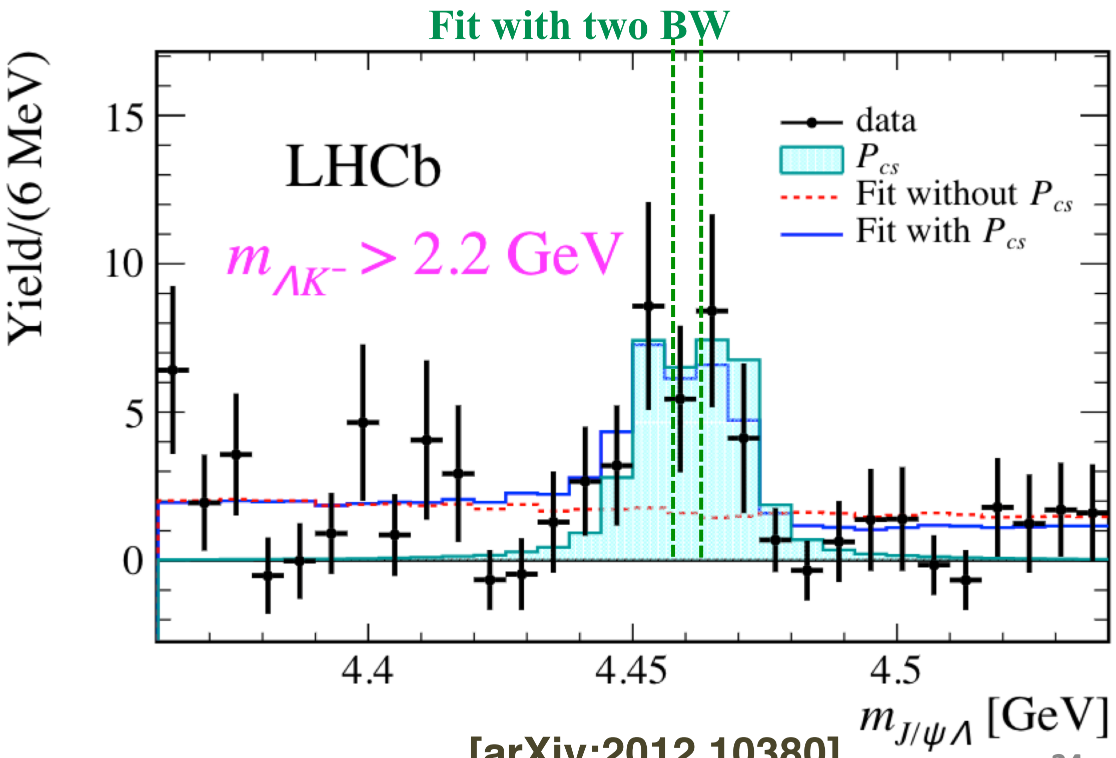
System	$[\Xi_c'\bar{D}]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c'\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c^*\bar{D}^*]_{\frac{3}{2}}$	$[\Xi_c^*\bar{D}^*]^\sharp_{\frac{5}{2}}$	$[\Xi_c\bar{D}]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{1}{2}}$	$[\Xi_c\bar{D}^*]_{\frac{3}{2}}$
ΔE	$-18.5^{+6.4}_{-6.8}$	$-15.6^{+6.4}_{-7.2}$	$-2.0^{+1.8}_{-3.3}$	$-7.5^{+4.2}_{-5.3}$	$-17.0^{+6.7}_{-7.5}$	$-8.0^{+4.5}_{-5.6}$	$-0.7^{+0.7}_{-2.2}$	$-13.3^{+2.8}_{-3.0}$	$-17.8^{+3.2}_{-3.3}$	$-11.8^{+2.8}_{-3.0}$
M	$4423.7^{+6.4}_{-6.8}$	$4568.7^{+6.4}_{-7.2}$	$4582.3^{+1.8}_{-3.3}$	$4502.9^{+4.2}_{-5.3}$	$4635.4^{+6.7}_{-7.5}$	$4644.4^{+4.5}_{-5.6}$	$4651.7^{+0.7}_{-2.2}$	$4319.4^{+2.8}_{-3.0}$	$4456.9^{+3.2}_{-3.3}$	$4463.0^{+2.8}_{-3.0}$

  - $J/\psi\Lambda, \bar{D}\Lambda_c^+ \ldots$ also exist in other models

- $P_{cs}(4459)^0$ mass close to $\Xi_c\bar{D}^*$ threshold, two $I = 0$ states with $\frac{1}{2}^-$ or $\frac{3}{2}^-$

  More data needed to resolve

- Confirmation by other states, decays

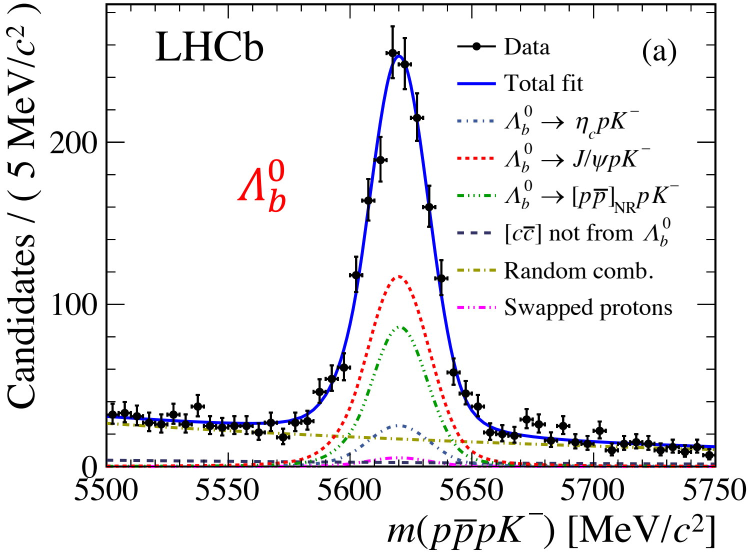


[arXiv:2012.10380]

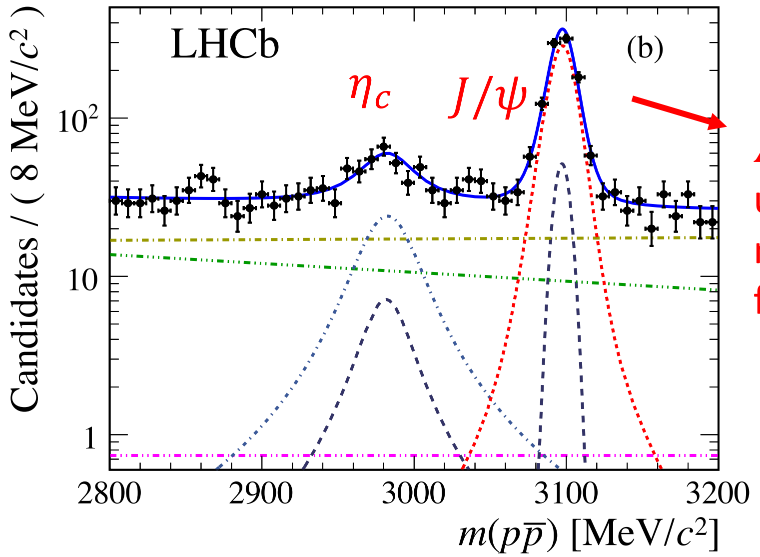
1st observation of $\Lambda_b^0 \to \eta_c p K^-$

[PRD 102 (2020) 112012]

- Same quark contents as $\Lambda_b^0 \to J/\psi p K^-$. Provide unique environment for P_c studies
- If $P_c(4312)^+$ is $\Sigma_c \bar{D}$ molecule, predicted $$\frac{\mathcal{B}(P_c(4312)^+ \to \eta_c p)}{\mathcal{B}(P_c(4312)^+ \to J/\psi p)} \sim 3$$
  [PRD 100 (2019) 034020, 100 (2019) 074007, 102 (2020) 036012]
- LHCb run2 data (5.5 fb^{-1})
  - η_c reconstructed using $\eta_c \to p\bar{p}$
- Fit 2D mass spectrum to confirm the existence



$\sim 170\ \Lambda_b^0 \to \eta_c p K^-$ signals



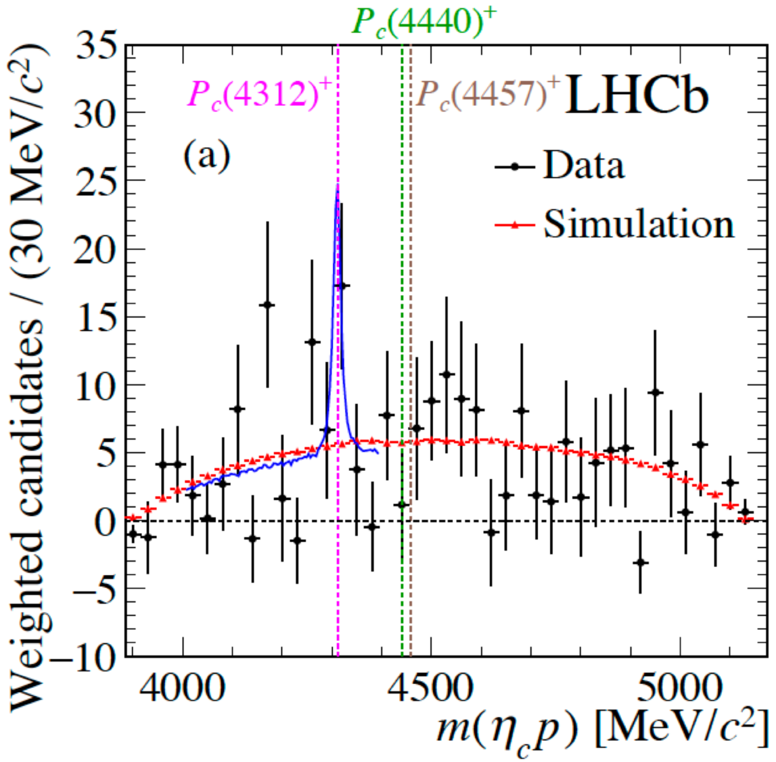
$\Lambda_b^0 \to J/\psi p K^-$ used as reference mode for branching fraction measurement

Search for P_c^+ in $\eta_c p$ system

[PRD 102 (2020) 112012]

- Check background-subtracted $\eta_c p$ mass spectrum
  - sPlot technique. 2D mass as discriminating variable.

No significant $P_c(4312)^+$ contribution (~2σ)



Relative P_c^+ production rates

$$R(P_c(4312)^+) < 0.24 \text{ @ } 95\% \text{ C. L.}$$

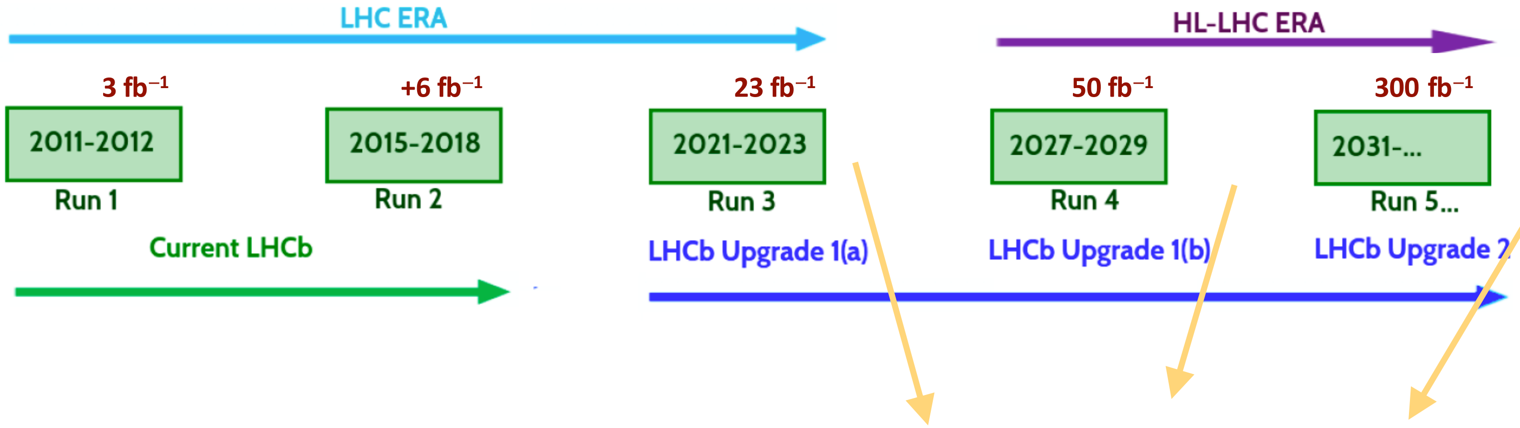
(Uncertainty is too large to give any conclusion yet)

- The $\Lambda_b^0 \to \eta_c p K^-$ branching fraction measured

$$\frac{\mathcal{B}(\Lambda_b^0 \to \eta_c p K^-)}{\mathcal{B}(\Lambda_b^0 \to J/\psi\, p K^-)} = 0.333 \pm 0.050\ (\text{stat.}) \pm 0.019\ (\text{syst.}) \pm 0.032\ (\mathcal{B})$$

Prospects

[arXiv:1808.08865]



Decay mode	LHCb 23 fb^{-1}	LHCb 50 fb^{-1}	LHCb 300 fb^{-1}
$B^+ \to X(3872)(\to J/\psi \pi^+\pi^-)K^+$	14k	30k	180k
$B^+ \to X(3872)(\to \psi(2S)\gamma)K^+$	500	1k	7k
$B^0 \to \psi(2S)K^-\pi^+$	340k	700k	4M
$B_c^+ \to D_s^+ D^0 \overline{D}^0$	10	20	100
$\Lambda_b^0 \to J/\psi\, pK^-$ [*]	680k	1.4M	8M
$\Xi_b^- \to J/\psi\, \Lambda K^-$	4k	10k	55k
$\Xi_{cc}^{++} \to \Lambda_c^+ K^-\pi^+\pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi\, \Xi_c^+$	50	100	600

- **LHCb is now boosting the data to a new level**
  - **Expect to 7x more data (14x hadronic events) by 2029 than current, half of these by 2023**
  - **Could have another 6x increase from Upgrade II**

$\chi_{c1}(3872)$ lineshape from multi-channels

$Z_c(4430)$, also explore $B \to D_{(s)}^{(*)}\overline{D}_{(s)}K^-$?

Doubly-charmed tetraquark $\mathcal{T}_{cc}^+ \to D_s^+ D^0$

More information for pentaquarks

[*] updated according to the latest result

Summary

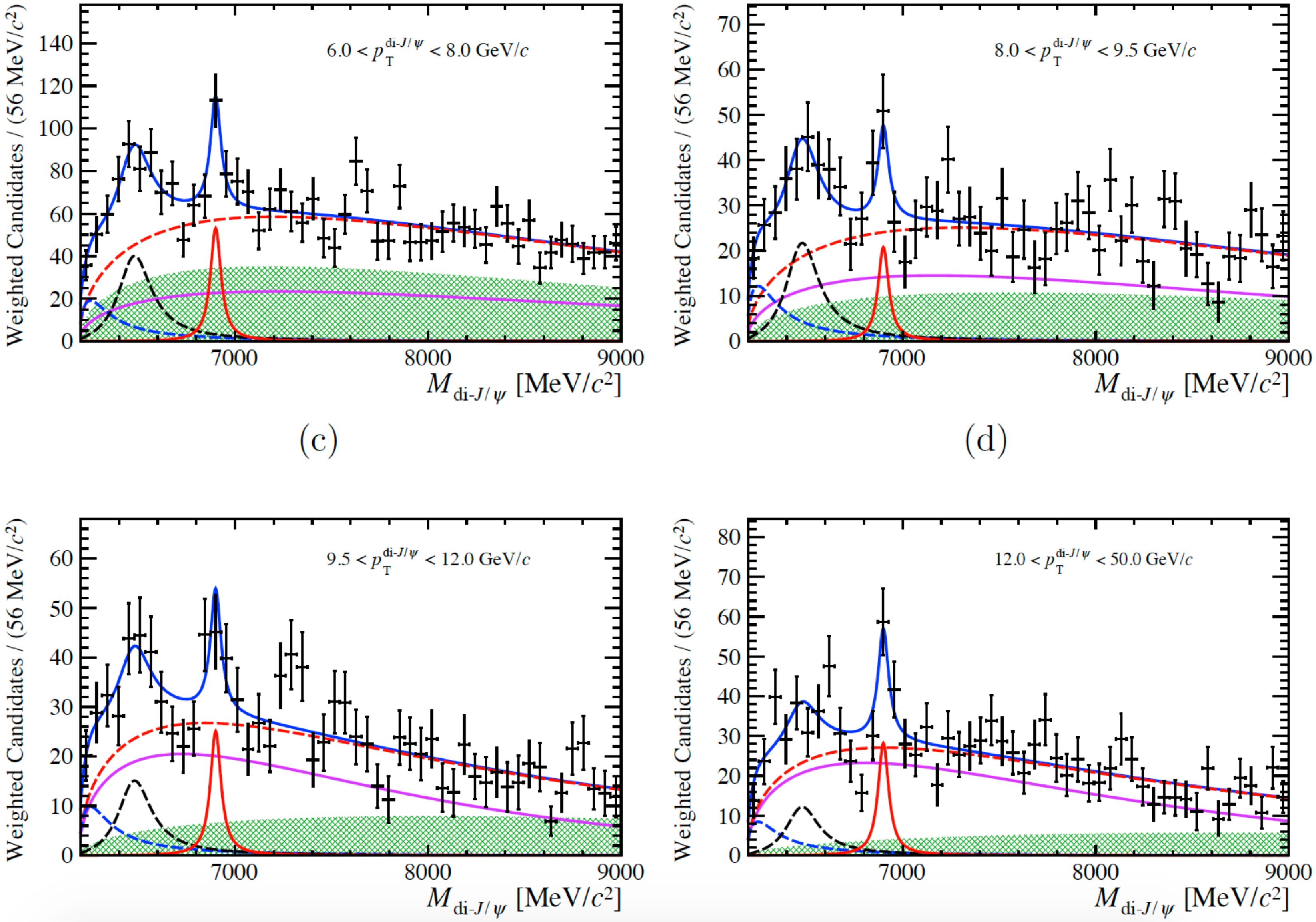
- LHC is a heavy-quark hadron factory, with LHCb detector dedicated for flavour physics, we can also
  - Explore meson and baryon excitation spectra
  - Study exotic hadron spectroscopy

- Many interesting results
  - Observations of first candidates for open-charm tetraquark $X_{0,1}(2900)$, full charmed tetraquark $X(6900)$
  - Evidence of first candidate for hidden-charm pentaquark with strangeness $P_{cs}(4459)^0$

Backup

$X(6900)$ in di-J/ψ system

[Science Bulletin 65 (2020) 032]



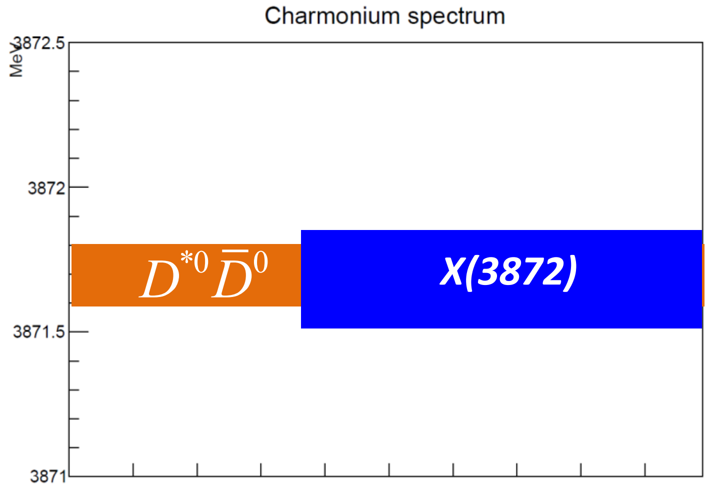
$X(3872)$ lineshape

- $X(3872)$ nature is still uncertain, although many studies are performed since 2003
  - $J^{PC} = 1^{++}$ [Phys. Rev. D92 (2015) 011102(R)]
  - **Mass = 3871.69 ± 0.17 MeV**
  - **Width < 1.2 MeV** @90% CL

$$\delta E = (m_{D^{*0}} + m_{D^0}) - m_{X(3872)} = 0.01 \pm 0.20 \text{ MeV}$$

[PDG 2020]

- Molecular interpretation requires $\delta E > 0$, the knowledge is limited by the mass precision of $X(3872)$
- Current precision is dominated by CDF results 10 years ago

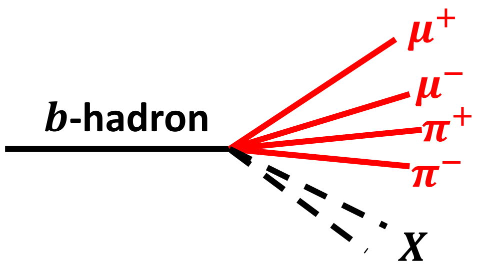


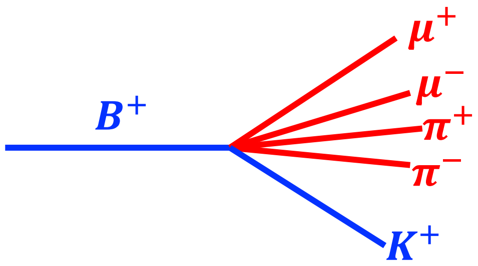
$\chi_{c1}(3872)$ MASS FROM $J/\psi X$ MODE

VALUE (MeV)	EVTS		DOCUMENT ID		TECN
3871.69 ± 0.17	**OUR AVERAGE**				
3871.9 ±0.7 ±0.2	20 ±5		ABLIKIM	2014	BES3
3871.95 ±0.48 ±0.12	0.6k		AAIJ	2012H	LHCB
3871.85 ±0.27 ±0.19	~ 170	1	CHOI	2011	BELL
3873 $^{+1.8}_{-1.6}$ ±1.3	27 ±8	2	DEL-AMO-SANCH..	2010B	BABR
3871.61 ±0.16 ±0.19	6k	3, 2	AALTONEN	2009AU	CDF2
3871.4 ±0.6 ±0.1	93.4		AUBERT	2008Y	BABR
3868.7 ±1.5 ±0.4	9.4		AUBERT	2008Y	BABR
3871.8 ±3.1 ±3.0	522	4, 2	ABAZOV	2004F	D0

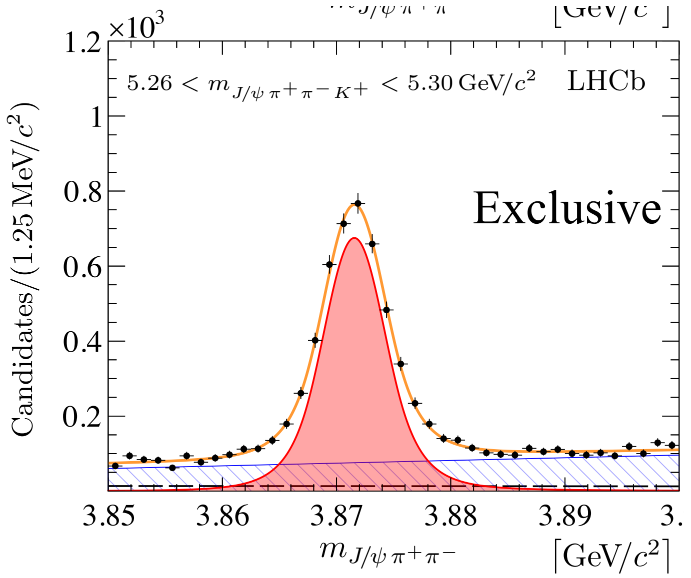
LHCb results with Breit-Wigner fit

- Two measurements using $X(3872) \to J/\psi\pi^+\pi^-$ related to $\psi(2S)$
  - Inclusive $b \to X(3872)$ + anything
  - Exclusive $B^+ \to X(3872)K^+$
- Mass resolution is 2-3 MeV





Meas.	Yield	M_{BW} (MeV)	Γ_{BW} (MeV)
Inclusive [arXiv:2005.13419]	~15.6k (more bkg)	$3871.695 \pm 0.067 \pm 0.068 \pm 0.010$	$1.39 \pm 0.24 \pm 0.10$
Exclusive [arXiv:2005.13422]	~4.2k (less bkg)	$3871.59 \pm 0.06 \pm 0.03 \pm 0.010$	$0.96^{+0.19}_{-0.18} \pm 0.21$



LHCb average

$$M_{BW} = 3871.64 \pm 0.06 \pm 0.01 \text{ MeV}; \Gamma_{BW} = 1.19 \pm 0.19 \text{ MeV}$$

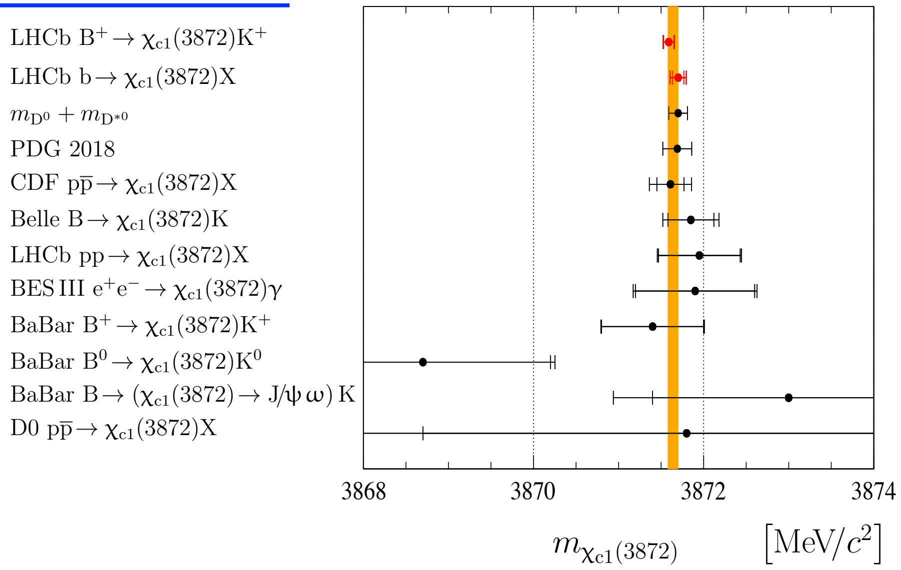
$$\delta E = M(D^0) + M(\bar{D}^{*0}) - M(\chi_{c1}(3872)) = 0.07 \pm 0.12 \text{ MeV}$$

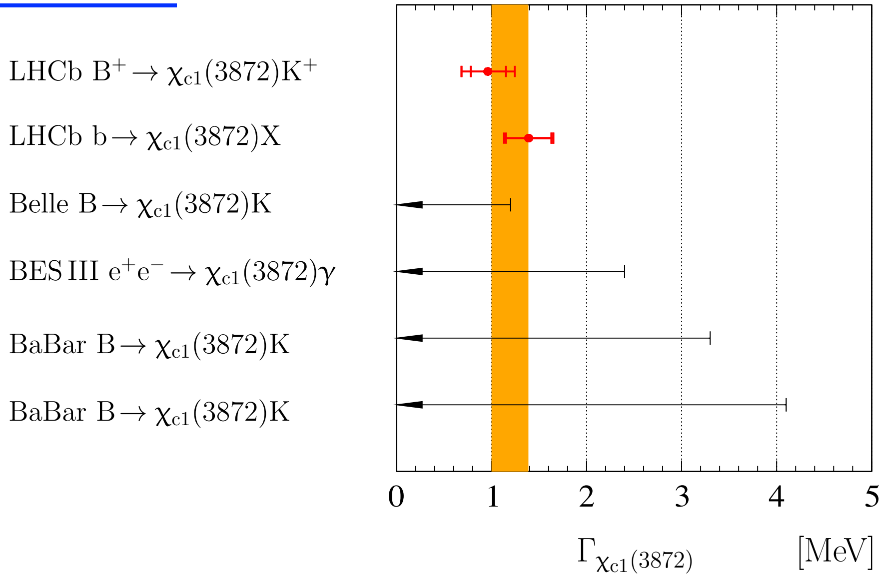
Flatté function also investigated, precision is limited by mass resolution

Uncertainty on δE is now dominated by knowledge of kaon masses

Breit-Wigner mass and width

[arXiv: 2005.13422]





- World average
  - ✓Before: $M_{\rm BW} = 3871.68 \pm 0.17\ {\rm MeV}/c^2$; $\Gamma_{\rm BW} < 1.2\ {\rm MeV}/c^2$ at 90% C.L.
  - ✓After: $M_{\rm BW} = 3871.64 \pm 0.06\ {\rm MeV}/c^2$; $\Gamma_{\rm BW} = 1.19 \pm 0.19\ {\rm MeV}/c^2$
- LHCb average
  - ✓$M_{\rm BW} = 3871.64 \pm 0.06 \pm 0.01\ {\rm MeV}/c^2$; $\Gamma_{\rm BW} = 1.19 \pm 0.19\ {\rm MeV}/c^2$
  - ✓$\delta E = M(D^0) + M(\overline{D}^{*0}) - M\big(\chi_{c1}(3872)\big) = 0.07 \pm 0.12\ {\rm MeV}/c^2$

*Small statistical overlap between the two samples is considered

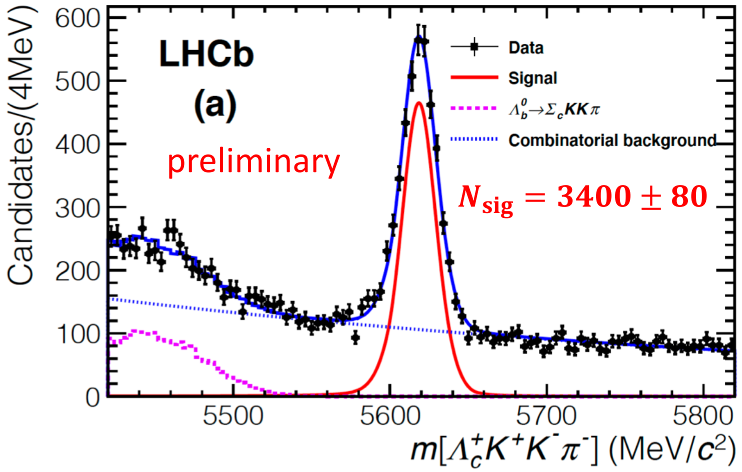
- Opening up of $D^0\overline{D}^{*0}$ threshold distorts the lineshape from Breit-Wigner ⇒

Search for pentaquark in $\Lambda_c^+ K^+$ system

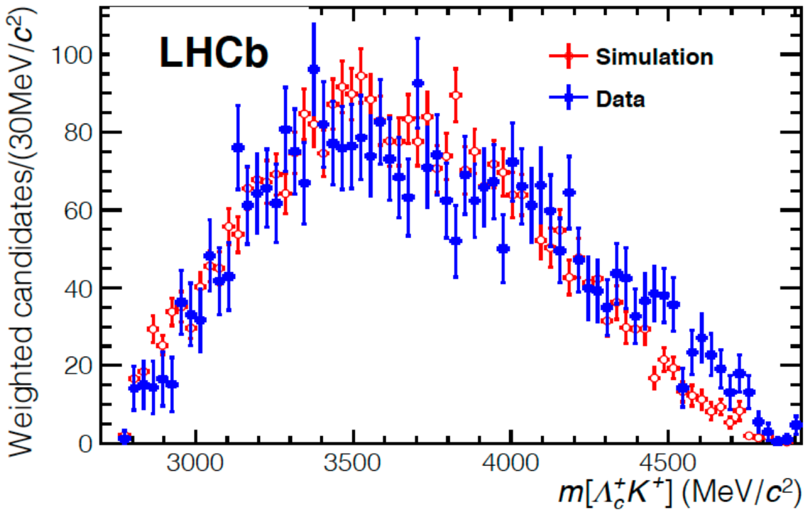
- Potential open-charm pentaquark $[c\bar{s}uud]$ decay to $\Lambda_c^+ K^+$
- Run1 data (3 fb^{-1})
  - Λ_c^+ reconstructed using $\Lambda_c^+ \to p K^- \pi^+$
  - $\Lambda_b^0 \to \Lambda_c^+ D_s^-$ used for normalization channel
- **1st observation of $\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-$**

$$\frac{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-)}{\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ D_s^-)} = (9.26 \pm 0.29 \pm 0.46 \pm 0.26) \times 10^{-2},$$

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ K^+ K^- \pi^-) = (1.02 \pm 0.03 \pm 0.05 \pm 0.10) \times 10^{-3}$$



- No excess observed in $m(\Lambda_c^+ K^+)$ spectrum
- Will search with more data and can also look for pentaquark $[c\bar{s}udd]$ in $\Lambda_c^+ K^+ \pi^-$ system



[arXiv:2011.13738]